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The SHADOWS experiment at the CERN SPS

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Abstract: SHADOWS (Search for Hidden And Dark Objects With the SPS) is a proposed proton beam-dump experiment for the search of a large variety of Feebly-Interacting Particles (FIPs) at the CERN SPS. It will exploit the potential for searches and discoveries at the intensity frontier offered by the upgrade of the ECN3 beam line. SHADOWS will be located off-axis, which allows the optimisation of the signal-to-background ratio, and will collect data from up to 5×10^{19} protons of 400 GeV on target in 4 years of operations. The experiment has a transversal size of $2.5 \times 2.5\,\mathrm{m}^2$ and is composed by an upstream veto, a 20 m long decay volume and a spectrometer with a tracking system in a dipole magnet, a timing detector, a calorimeter and a muon system. The conceived detector offers excellent tracking and timing performance for the identification and reconstruction of most of the visible final states of FIP decays. SHADOWS will allow to explore a large parameter space region of many FIPs, like light dark scalars, axion-like particles and heavy neutral leptons, with masses ranging between 0.1 and 10 GeV. This paper reports about the status of the proposal of the SHADOWS experiment, with focus on the detector challenges.

Keywords: Dark Matter detectors (WIMPs, axions, etc.); Spectrometers

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Contents

1 Introduction

Feebly-interacting particles (FIPs) with masses below the electro-weak scale and possibly belonging to a rich dark sector represent a complementary approach with respect to the traditional Beyond the Standard Model physics explored at the LHC. They can provide an answer to many open questions in modern particle physics: the baryon asymmetry of the universe, the nature of dark matter (DM), the origin of the neutrino masses and oscillations, the cosmological inflation, the strong CP problem, and the hierarchy of scales [1].

SHADOWS (Search for Hidden And Dark Objects With the SPS) is a proposed proton beam-dump experiment for the search of a large variety of FIPs in the energy range from MeV to a few GeV, at the CERN SPS. It aims at exploiting the existing infrastructure and accelerator complex of the CERN North Area, namely the ECN3/TCC8 experimental complex currently hosting the NA62 experiment, and the 400 GeV proton beam line P42.

2 Experiment overview

The SHADOWS detector requirements are determined by the characteristics of the FIPs produced in the interactions of the SPS 400 GeV/c proton beam with a dump. FIPs with masses above the kaon mass primarily result from decays of charmed and beauty hadrons, as well as proton Bremsstrahlung and/or the Primakoff effect in the dump. An off-axis detector design is crucial due to the large polar angles of FIPs produced at the center-of-mass energy ($\sqrt{s} \sim 28$ GeV) of the beam dump collision. The detector's distance from the proton beam impact point on the dump balances the need to maximize FIP flux (requiring short distances) and the probability that FIPs decay before reaching the detector (requiring long distances), which depend on FIP models and benchmarks.

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The SHADOWS detector must be able to reconstruct and identify most of the visible final states of FIPs decays. These are listed in table 1 for the main portals for a FIP in the MeV-GeV mass range [2].

Table 1. Main decay modes for FIPs in the MeV-GeV mass range. $\ell = e, \mu, \tau$ [2].

Scalar portal	$\ell^+\ell^-, \pi^+\pi^-, K^+K^-$
Pseudo-scalar portal	$\ell^+\ell^-, \gamma\gamma, \pi^+\pi^-, K^+K^-$
Vector portal	$\ell^+\ell^-, \pi^+\pi^-, K^+K^-$
Fermion (neutrino) portal	$\ell^\pm\pi^\mp, \ell^\pm K^\mp, \ell^\pm\rho^\mp\left(\rho^\mp \to \pi^\pm\pi^0\right), \ell^+\ell^-\nu$

In order to reach the sensitivities described in section 10, a powerful proton beam is required. As a baseline scenario, SHADOWS will run in parallel with the proposed HIKE experiment [3] when the K12 beam-line is operated in Beam Dump mode. SHADOWS will be installed off-axis on the Jura side (i.e. towards the left when looking the beam direction) of the K12 beam line. The SHADOWS detector in the TCC8 tunnel, close to the shielded target area is shown in figure 1.

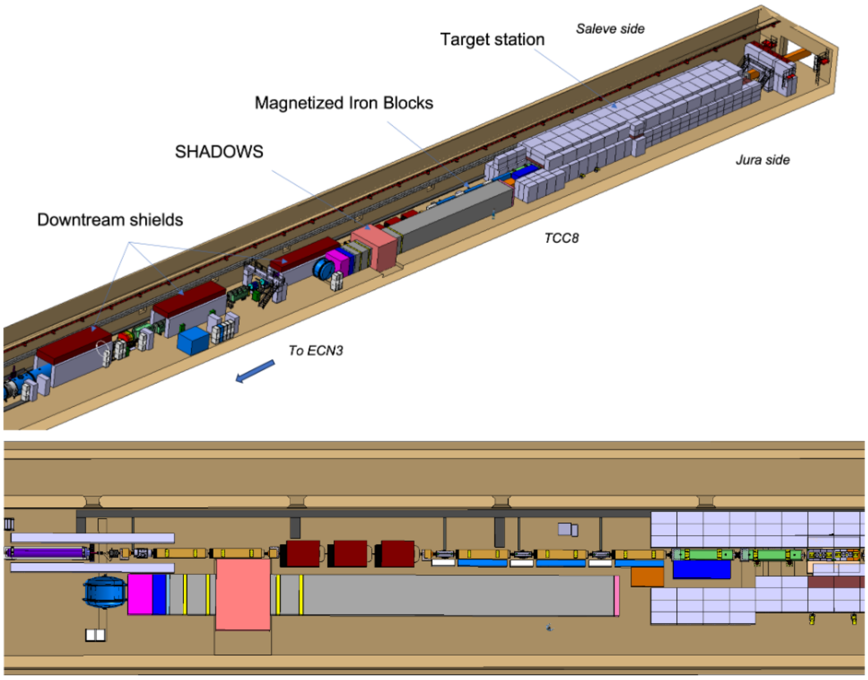

Figure 1. 3D and top view of the SHADOWS detector integrated into the experimental area and target station.

The K12 beam line is derived from the P42 beam, a 400 GeV/c primary proton beam impinging on a 400 mm long, 2 mm diameter cylindrical Beryllium target (T10) that is used to produce a secondary positively charged hadron beam of 75 GeV/c momentum. In beam dump mode, the T10 target is lifted and the proton beam is fully dumped onto the NA62 dump collimators that act as a hadron stopper ~ 23 m downstream the target.

The P42 beam currently delivers $3 \cdot 10^{12}$ protons per 4.8-second SPS spill onto the T10 target for NA62. For SHADOWS and HIKE operation an upgrade of $2 \cdot 10^{13}$ per spill has been proposed, more than 6 times higher than the nominal intensity. Therefore, SHADOWS in this location will collect $5 \cdot 10^{19}$ protons on target in 4 years of operation [4]. A conceptual layout of SHADOWS detector is shown in figure 2.

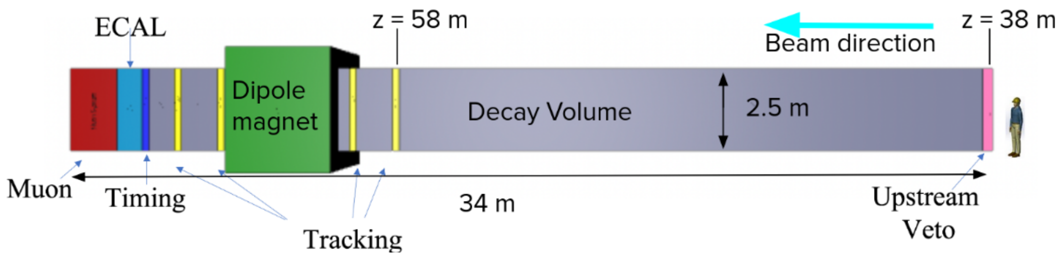

Figure 2. Lateral view of the SHADOWS detector layout.

Muons and neutrinos emerging from the dump are the two major sources of background for FIP searches in SHADOWS. Muons pose challenges by generating both combinatorial background and inelastic interactions in the last interaction lengths of the dump collimator, K12 beamline elements, and the decay vessel material. The combinatorial muon background arises from random combinations of opposite-charged muon tracks entering the decay vessel, mimicking di-muon final state events and forming a fake vertex in the fiducial volume. On the other hand, inelastic muon interactions occur as muons interact with material, either upstream or on the decay vessel, generating particles, including those that generate a decay vertex in the decay volume (K_S, K_L, and Λ) and can therefore mimic the signal events listed in table 1. Moreover, neutrinos emerging from a proton beam dump can make inelastic interactions with the beamline and detector material, in particular with the decay vessel. They are mostly produced by the decay of light mesons, pions and kaons.

SHADOWS off-axis design minimizes the impact of muon and neutrino backgrounds, which are concentrated in the forward region. Transverse distance considerations involve a compromise between signal acceptance loss and background reduction. The decay volume starts at 38.05 m from the T10 target ($\sim$ 15 m from the dump), spanning 19 m. The transverse dimensions are $2.7 \times 2.7\,\mathrm{m}^2$ with a $2.5 \times 2.5\,\mathrm{m}^2$ active area. The expected rate of muon background over the whole SHADOWS acceptance is $\sim$ 150 MHz, which is further reduced by the muon sweeping system, detailed in the next section. Neutrinos are mostly produced in the very forward region, and only 7% of the overall neutrino flux enters the SHADOWS acceptance. Considering an average interaction probability of $6 \cdot 10^{-12}$ for inelastic scattering, the probability of one neutrino interaction is $8 \cdot 10^{-5}$ per spill.

3 The muon sweeping system

The SHADOWS muon sweeping system aims to reduce the muon background at the detector. Muons originating from the beam dump are diverted off-axis in the SHADOWS acceptance by the return yokes of two dipole magnets downstream the dump.

Muons from the dump can be mitigated in two ways: passive mitigation, where muons lose energy and are absorbed by a dense material; and active mitigation, using magnetic fields to divert muons away from detectors. The SHADOWS muon sweeping system employs both methods with magnetized iron blocks (MIBs) between the beam dump and the detector, and is shown in figure 3. A first magnetized block (Stage 1), located alongside the second dipole magnet donwstream the beam dump, separates positive and negative muons. Stage 2 is made of three MIBs with the same design, which are interleaved by three non-magnetised iron blocks that serve as passive shielding. Stage 2 is placed directly after Stage 1 to push the separated muons away from the detector region immediately. Stage 3 is a magnetized iron block placed in front of the decay vessel alongside the first few meters of the slim Stage 2 MIBs. This enables to also actively sweep the remaining background that is too far off-axis to be in the acceptance of Stage 2.

An overall reduction factor of the muon flux of about 70 is observed at the level of the first tracking chamber for muons above 3 GeV, bringing down the rate from 150 MHz to about 2 MHz in the full SHADOWS acceptance.

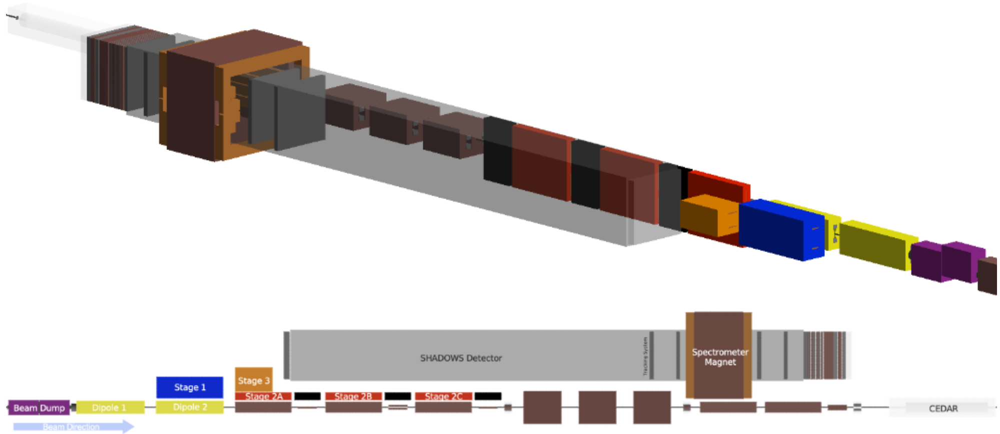

Figure 3. SHADOWS MIB system placed along the K12 beamline. Stage 1 block is shown in blue, Stage 2 magnetized blocks are red and non-magnetized ones are black, Stage 3 is orange.

4 Decay vessel and vetoes

The SHADOWS experiment employs a low-pressure vacuum tank (1 mbar) to minimize neutrino-induced background events in the decay volume. Neutrino interactions mainly occur in the vessel walls, allowing easy rejection based on criteria related to the impact parameter at the proton target. The upstream and lateral veto system further suppresses the residual interactions.

The vacuum vessel has a modular design, with a squared aperture of $2.5\,\text{m} \times 2.5\,\text{m}$, and 19 m length, and will contain the dipole magnet and tracking system.

The veto detector of SHADOWS is located upstream and on the beam-facing side of the decay vessel and has to guarantee the effective rejection of events from charged particles (fully dominated by muons of both charges) originated by proton collisions on target. It consists of two independent layers of modules of resistive Micromegas with pad readout [5], built using the bulk technique with an active area up to of $100 \times 50\,\text{cm}^2$. The combined efficiency of two detector layers, each of them with an efficiency of 98%, is $> 99.9\%$.

5 Tracking system and dipole magnet

The SHADOWS tracking and spectrometer system aims to accurately reconstruct charged particle tracks and measure their momenta. By backward extrapolating particle tracks into the decay volume, the system can reconstruct the decay vertex of potential FIP candidates. Additionally, the system estimates the mass of the FIP candidate from particle momenta. The spectrometer consists of two tracking stations upstream and downstream of the dipole magnet (figure 4). Each tracking stations has two stereo-layers each measuring the coordinates in the x and y direction.

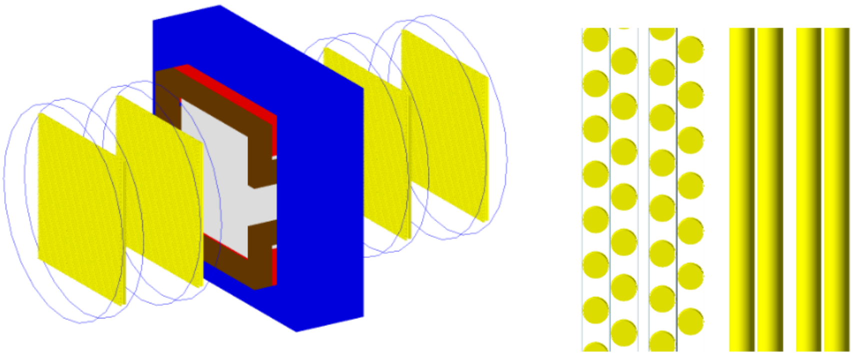

Figure 4. Arrangement of the 8 stereo-layers in two stations up-stream and 2 stations downstream of the dipole magnet. Center: cross-section through the two stereo-layers of one station. The arrangement of the straw tubes into four individual layers with a spacing of about 1 cm is shown.

The dipole magnet has an aperture of $2.7 \times 2.7\,\mathrm{m}^2$ and provides a field integral of 1 Tm in the vertical direction. The baseline technology for this dipole is a warm magnet, but a superconducting option is being investigated as well. For the tracking station the baseline technology consists in straw tubes with 1 cm diameter as used for the NA62 tracker [6]. Scintillating fibers read out by silicon photomultipliers (SiPMs) are also under investigation.

6 Timing detector

The timing detector has to provide a time resolution of $O(100\text{–}150)$ ps to reject combinatorial backgrounds made of out-of-time charged tracks, mostly muons.

Plastic scintillator bars of $1.26\,\mathrm{m} \times 6\,\mathrm{cm} \times 1\,\mathrm{cm}$ read out by an array of 8 SiPMs will be employed. A time resolution of ~ 80 ps almost uniform along the bar length has been demonstrated on prototypes [7].

7 Electromagnetic calorimeter

The electromagnetic calorimeter must be able to reconstruct the energy, the position and (possibly) the direction of photons coming from FIP decays, either directly or via intermediate resonances (e.g. $\pi^0 s$). An energy resolution of about $\sigma(E)/E \sim 10\text{–}15\%/\sqrt{E(\mathrm{GeV})}$, with longitudinal segmentation for pointing capabilities is required.

In the baseline design, the ECAL is a $2.5\,\mathrm{m} \times 2.5\,\mathrm{m}$ iron-scintillator sandwich calorimeter, 20 X_0 deep to prevent shower leakage up to energies in the tens of GeV range. It comprises 40 iron layers, each 9 mm thick (about 0.5 X_0), and 40 active layers, with each layer containing 250 plastic-scintillator strips ($250 \times 1 \times 1\,\mathrm{cm}^3$) arranged alternately in horizontal and vertical directions. The light is read out using one WLS fiber per strip, connected to one SiPM at each end, resulting in 500 SiPMs and readout channels per scintillator layer. The use of WLS fiber readout allows for the use of polystyrene-based scintillators with a modest attenuation length.

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8 Muon detector

The muon system primarily serves to identify muons with high efficiency (> 95%) and achieve a subsequent reduction of hadron contamination to less than 1% in a momentum range of 5–100 GeV/c. Additionally, it complements the timing detector by effectively rejecting combinatorial muon background pairs from the beam muon halo through tight time coincidence of the two tracks within a $3\sigma_t$ window, with $\sigma_t \sim 150$–200 ps.

The muon system will consist in three active stations, with an active area of 2.5×2.5 m^2, interleaved by two iron filters about 30 cm thick, and shielded by an iron shield 50 cm thick. In order to achieve the required time resolution, over the three stations, a time resolution of ~ 250–300 ps per station is required.

The fundamental active element of the muon detector is a $150 \times 150 \times 10$ mm^3 plastic scintillator tile, read out by four SiPMs [8]. These tiles are organized into modules of 16 or 32 tiles each. Each station incorporates 16 or 8 modules, arranged in a staggered chequerboard pattern on both sides of a supporting structure. A schematic layout of the SHADOWS muon system is shown in figure 5.

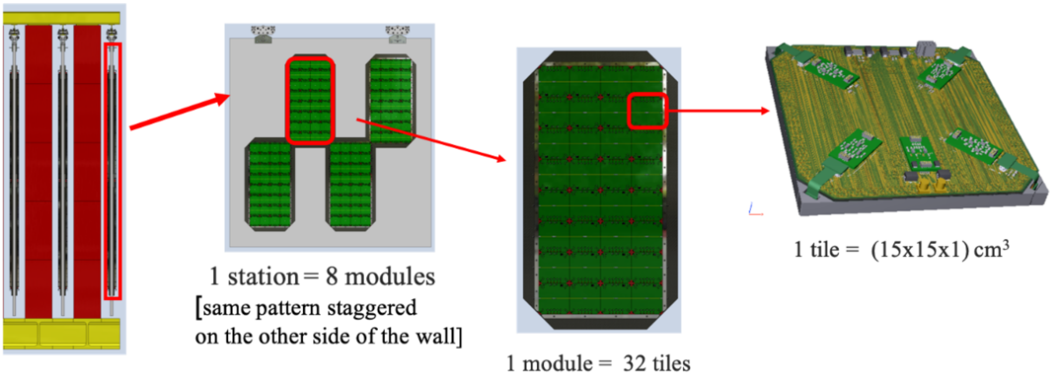

Figure 5. Schematic layout of the SHADOWS muon system, consisting of three active stations interleaved with passive filters. Each station comprises 8 or 16 modules, with 16 or 32 tiles each, organized in a chequerboard pattern. Each tile covers ~ 225 cm^2.

9 Background estimation

Studies on the muon background have been performed on a simulated sample of $5\cdot10^9$ protons-on-target (pot). To generate a sufficient statistic a biasing method has been used, which was developed by the NA62 collaboration [9]. The statistical power of this sample is equivalent to $N_{\text{pot}} \sim 3\cdot10^{13}$ for combinatorial studies (due to the biasing technique) and to $N_{\text{pot}} \sim 2\cdot10^{21}$ (about 40 times the full SHADOWS dataset) for the inelastic interactions study, as the muons are forced to interact with the material with 100% probability, while this probability is on average 1.4×10^{-8}.

The combinatorial muon background is addressed through several stringent requirements. Firstly, the timing detector plays a pivotal role for combinatorial muons by imposing a time window of $\delta T = \pm3\sigma_t$, where $\sigma_t \sim 100$ ps is the assumed time resolution of the timing layer, resulting in a rate of accidental pairs of ~ 600 s^{-1}. This leads to approximately 3000 accidental pairs per 4.8 s long spill. Further mitigations involve the upstream and lateral veto system, with an anticipated efficiency of 99.8%. The probability of not vetoing two muon tracks emerging from the dump is calculated to be $(1-\epsilon)^2 = 4\cdot10^{-6}$, yielding $N_{\mu\mu}$ (timing, not vetoed) $\sim 1.2\cdot10^{-2}$ /spill. Thirdly, vertex requirements, involving the closest approach distance (CDA), are implemented to ensure reconstructed vertices lie within the decay volume, reducing the combinatorial background by $P(CDA) = 5 \cdot 10^{-4}$, resulting in $N_{\mu\mu}$ (timing, not vetoed, CDA) $\sim 6 \cdot 10^{-6}$/spill. Finally, a pointing requirement is enforced, reducing the combinatorial background further by $P(\mathrm{IP} < 6\ \mathrm{cm}) = 1 \cdot 10^{-4}$, yielding $N_{\mu\mu}$ (timing, not vetoed, CDA, IP) $\sim 6 \cdot 10^{-10}$/spill.

For the inelastic muon component, the probability of muons interacting with the decay vessel walls is $P = 1.4 \cdot 10^{-8}$, yielding an average of approximately 7.5 particles per interaction. The number of inelastic muon interactions not detected by the veto system is $1.8 \cdot 10^{-3}$/spill, which is further reduced by applying the requirement on the vertex and the impact parameter to $1.1 \cdot 10^{-8}$/spill for fully reconstructed signal events, and to $3.6 \cdot 10^{-7}$/spill for partially reconstructed ones.

Predominantly originating from the decay of light mesons, pions, and kaons, with only a minor contribution from charm decays, neutrinos pose less concern in an off-axis setup due to their forward direction and reduced momentum. Of the approximately $6.8 \cdot 10^{10}$ neutrinos produced in a $2 \cdot 10^{13}$ pot spill, only 7% enter the SHADOWS decay volume, resulting in approximately $5 \cdot 10^{9}$ $(\nu + \bar{\nu})$ per spill or $1.5 \cdot 10^{16}$ $(\nu + \bar{\nu})$ over the expected $\sim 3 \cdot 10^{6}$ spills in the SHADOWS lifetime. Given the probability of having one neutrino inelastic interaction per spill of $\sim 8 \cdot 10^{-5}$ and the requirements to have at least two tracks releasing hits in the first tracking chamber and with $p > 3$ GeV, the probability to have a "visible" neutrino interactions is down to less than $4 \cdot 10^{-9}$ per spill, less than 0.01 events over the entire SHADOWS lifetime.

Table 2 summarises the estimated background events in the whole SHADOWS lifetime, corresponding to $5 \cdot 10^{19}$ pot or $2.4 \cdot 10^{6}$ spills, for fully reconstructed and partially reconstructed final states. Summing up all the components, SHADOWS will have less than 1 background event in the full data set.

Table 2. Estimated background events in $5 \cdot 10^{19}$ protons on target [4].

background type	fully reconstructed	partially reconstructed
combinatorial di-muon	0.001	0.7
muon inelastic interactions	< 0.025	< 0.90
neutrino inelastic interactions	< 0.01	< 0.01

10 Physics reach

The SHADOWS experiment, designed with an off-axis configuration, exhibits notable sensitivity to FIPs produced in the decay of mesons and baryons containing heavy quarks. The physics reach of SHADOWS is assessed based on the anticipated $5 \cdot 10^{19}$ proton-on-dump events. The sensitivity curves shown in this section for SHADOWS and other experiments are presented as 90% CL exclusion bounds.

Figure 6 displays SHADOWS sensitivities for dark scalars and ALPs with fermion couplings. SHADOWS can improve by three orders of magnitude over the existing bounds, primarly from LHCb, between the di-muon threshold and ~ 4 GeV for the former, and about two orders of magnitude for the latter. Moreover, SHADOWS is fully complementary to HIKE-phase 1 in kaon mode, covering a range from below the kaon mass up to the B mass, depending on the model and scenario. The combined SHADOWS + HIKE system's uniqueness lies in its ability to explore new light and feebly-interacting phenomena while simultaneously probing very high-scale masses through precision measurements in the kaon sector.

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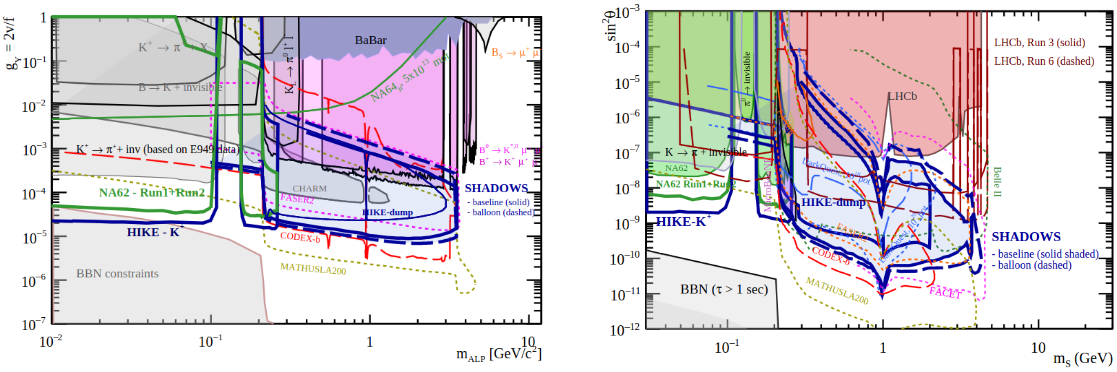

Figure 6. SHADOWS sensitivity to ALPs (left) and dark scalars (right) with fermion couplings at 90% CL exclusion limit (solid thick blue curve with shaded light blue area). HIKE-phase1 sensitivity at 90% CL exclusion limit (solid thick blue curve with no shaded area).

Figure 7 shows SHADOWS sensitivities for Heavy Neutral Leptons with single flavor dominance. For electron-coupled HNLs, SHADOWS achieves an improvement by approximately four orders of magnitude between the kaon and charm thresholds and more than one order of magnitude between the charm and beauty thresholds. In the case of muon-coupled HNLs, SHADOWS excels by over one

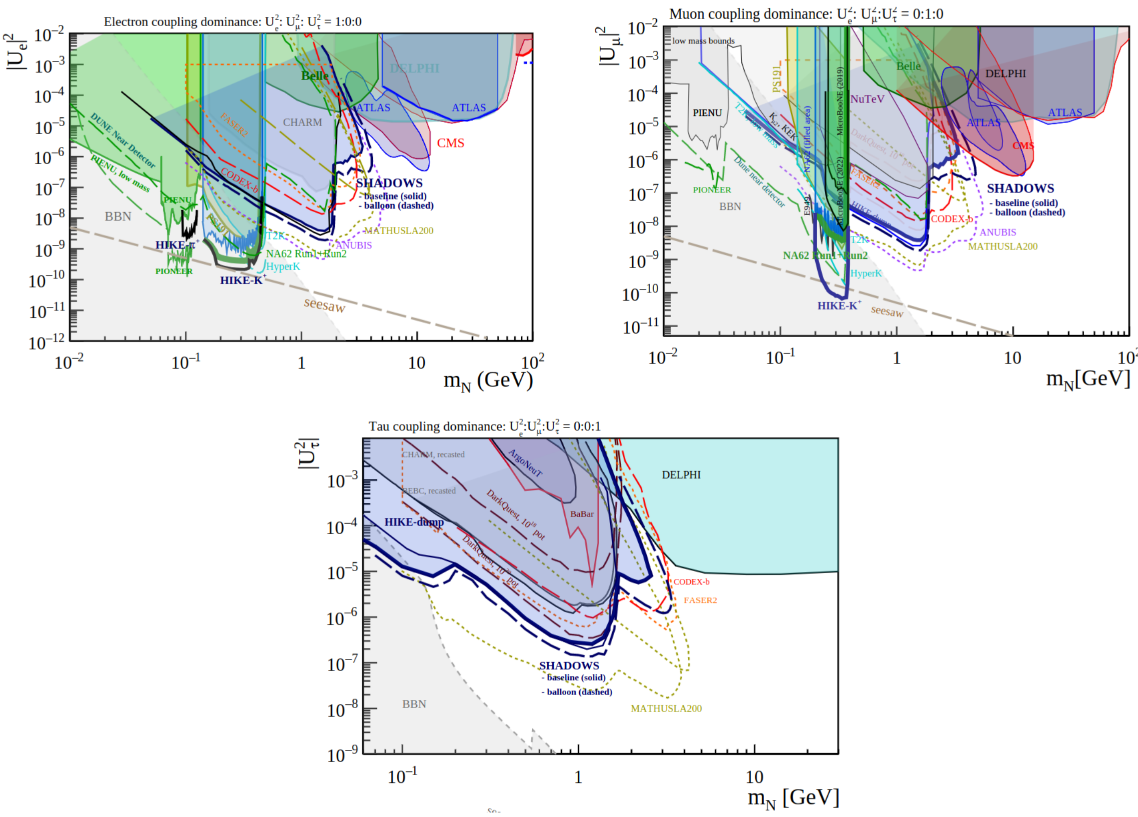

Figure 7. SHADOWS sensitivity to Heavy Neutral Leptons with single flavor dominance couplings at 90% CL exclusion limit (solid thick blue curve with shaded light blue area) for electron dominated couplings (top left), muon couplings (top right), tau couplings (bottom).

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order of magnitude below the charm threshold and achieves one order of magnitude improvement over CMS above the charm threshold. For tau-coupled HNLs, SHADOWS improves the current limits by more than three orders of magnitude below the charm threshold and by over two orders of magnitude between the charm and beauty thresholds.

11 Conclusions

In recent years, there has been a growing focus on feebly-interacting particles (FIPs) and the dark sector within the high-energy physics community, driven by both existing data and the need for extensions to the Standard Model. The MeV-GeV scale, particularly underexplored, has become a key area of interest. The concurrent operation of SHADOWS and HIKE, covering complementary FIP parameter ranges above and below the kaon mass, will significantly contribute to exploring and understanding FIP physics globally.

If the SHADOWS technical proposal secures approval in early 2024, the envisioned timeline for construction initiation is in 2027 with a first run by 2030–2031. Over the subsequent eight years, data collection will occur, alternating between kaon and beam-dump modes.

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